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Field Demonstration of a Broadband Acoustical Backscattering System Mounted on a REMUS-100 for Inferences of Zooplankton Size and Abundancy

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LONG-TERM GOALS

The long term goal of this research is to develop high-frequency broadband acoustical scattering techniques to remotely and autonomously characterize zooplankton distribution, size, abundance, and community structure, on ecologically relevant spatial and temporal scales. In order to achieve this goal, an autonomous, compact, low-power, high-frequency, broadband acoustical backscattering system suitable for use from gliders and small powered AUVs has been developed and mounted on a REMUS-100.

OBJECTIVES

The specific objective of the work proposed here is to assess the performance of this REMUS-mounted broadband backscattering system with regards to inferring zooplankton size and abundance in comparison to existing, cabled, high-power acoustic systems and more traditional sampling

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systems, namely a MOCNESS net sampling system and a Video Plankton Recorder (VPR) optical sampling system.

APPROACH

Over the last 40 years, there has been significant research effort directed at using high-frequency acoustic scattering techniques to remotely investigate the distribution, abundance, and size of marine organisms (Simmonds and MacLennan, 2005, and references therein). In fact, some of the world's largest stocks of zooplankton, such as Antarctic Krill (Nicol and Endo, 1999), as well as large fish stocks, are assessed using single or multi-frequency narrowband acoustic scattering techniques (Simmonds and MacLennan, 2005). Acoustic scattering techniques provide a rapid, high-resolution, synoptic, remote sensing alternative to more traditional sampling strategies. Yet reducing the ambiguities in the quantitative interpretation of the acoustic returns, with the ultimate goal of accurate, remote classification and quantification of scattering sources, remains one of the outstanding challenges.

The use of high-frequency narrowband acoustic scattering techniques have become relatively routine for synoptic studies of zooplankton populations (Wiebe *et al.,* 1996, 1997; Brierley *et al.*, 1998; Pieper *et al.*, 2001; Lawson *et al.*, 2004, 2008a,b; Lavery *et al*., 2007). Although traditional single-narrowband-frequency echosounders are frequently used for visualizing zooplankton populations, there remain inherent difficulties associated with the interpretation of the acoustic scattering returns even when direct and coincident measurements of the scattering sources are available. In principle, measurements of high-frequency acoustic scattering from zooplankton across a broad range of frequencies, spanning multiple octaves of bandwidth, can reduce the ambiguities typically associated to the interpretation of acoustic scattering at a single frequency or a limited number of discrete narrowband frequencies. The goal is to capitalize on the different characteristic frequency-dependent spectra associated to different scattering sources. The potential for this technique is supported by broadband measurements on caged aggregations of fish (e.g. Simmonds and Armstrong, 1990; Simmonds *et al.,* 1996), free-swimming individual fish (e.g. Lundgren and Nielsen, 2008), and numerous broadband laboratory measurements of fish (e.g. Reeder *et al,* 2004; Au and Benoit-Bird, 2008), squid (e.g. Lee *et al.*, 2009), zooplankton (e.g. Roberts and Jaffe, 2008), and different types of microstructure (e.g. Goodman and Oeschger, 2003; Lavery and Ross, 2007), as well as the fact that many toothed whales use broadband echolocation signals to detect and classify their prey (Au *et al.,* 2009). In addition to increased spectral coverage, an advantage to using broadband acoustics is that pulse compression signal processing techniques (Chu and Stanton, 1998) can be used that capitalize on the broadband nature of the transmitted waveform and can result in improved signal-to-noise ratios and range-resolution. However, there are a very limited number of high-frequency broadband acoustic scattering measurements in the field.

There are only a few commercially available (Ross and Lawson, 2009: 85–155 kHz, slightly less than octave bandwidth), or custom-built prototype (Foote *et al.*, 2005: 25 kHz to 3.2 MHz using seven octave bandwidth transducers), high-frequency broadband acoustic backscattering systems that have been used for studying zooplankton and/or microstructure in the field. In contrast, lower-frequency broadband scattering measurements (< 120 kHz) to remotely characterize fish have been performed more prevalently (e.g. Zakharia et al., 1996; Stanton *et al.*, 2010), including measurements involving explosives (e.g. Holliday, 1972; Thompson and Love, 1996; Nero *et al.,* 1998; Love *et al.*, 2004). Broadband techniques have been successfully adapted for field measurements of zooplankton and microstructure by Lavery and colleagues (Lavery *et al.*, 2010a,b), using a high-powered, cabled system developed by Edgetech.

To date, low-cost, compact, autonomous, low-power, broadband acoustic backscattering systems, spanning multiple octaves of bandwidth, appropriate for studies of zooplankton ecology from autonomous platforms have not been available. Autonomous vehicles, such as gliders and AUVs, offer advantages in persistence and spatial coverage that can improve our ability to synoptically understand important ecological systems, such as thin layers and baleen whale habitats. Although many autonomous vehicles carry an ADCP, which provides a crude measure of a backscatter at a single narrowband frequency, and some AUVs carry single-frequency sidescan sonars (and this technology has been adapted for gliders), the lack of suitable instrumentation has impeded the use of more sophisticated broadband techniques from these vehicles for zooplankton and fish applications.

The research performed here combines the power of two emerging technologies: broadband acoustical backscattering techniques and autonomous vehicles. This combination has the potential to enhance current capabilities for assessing zooplankton distribution, size, and abundance across ecologically relevant spatial and temporal scales. An autonomous, low-power, compact, high-frequency broadband acoustical backscattering system, covering the frequency range from 120 khz to 1.25 MHz, and employing only 1.5 Watts of power, has been fabricated with prior ONR MMB funding. It is based on a monostatic Doppler sonar module recently developed at WHOI (Jaffre et al., 2010) and its basic function has been tested in the Connecticut River in the context of measuring scattering from salinity microstructure in November 2008 and 2009, with coincident measurements of turbulence and salinity microstructure. However, its performance in relation to determining zooplankton size and abundance was untested. The overarching goal of this project is to measure broadband acoustical backscattering from different assemblages of zooplankton using the WHOI broadband scattering system mounted on the REMUS-100. The specific goal is to complete the modifications and assembly of the REMUS-100 broadband zooplankton module, calibrate the system on the REUS-100, assess the performance of this system in the field, in terms of all system parameters, including noise, range, and ability to infer zooplankton size and abundance, in comparison to both direct groundtruthing measurements and other broadband and/or multi-frequency acoustical backscattering systems. Ideally, the system performance will be assessed in the context of different zooplankton and/or fish assemblages with different frequency responses, including small non-gas-bearing zooplankton for which the Rayleigh-to-geometric scattering transition is within the frequency band of the WHOI broadband system (e.g., copepods), and either larger fluid-like zooplankton (e.g., euphausiids) or organisms with gas-inclusions (e.g., fish, siphonophores), for which the Rayleigh-to-geometric scattering transition or resonance frequency is below the frequency band of the WHOI broadband system.

WORK COMPLETED

The development of the REMUS-100 bioacoustics module has been completed (Fig. 1) and the system has been calibrated (Fig. 2), while mounted on the REMUS-100, in a 3-m-deep, salt-water tank at WHOI using a 8.9-mm and 21.2-mm diameter tungsten carbide (WC) standard targets. Details of the system, including power requirements, size, and beamwidths are given in previous

ONR progress reports. The system was further tested on short missions in the Woods Hole harbor and in the WHOI sea well prior to the field demonstrations.

The REMUS-100 bioacoustics module was deployed on 17 missions during a 3-day cruise in and around Stellwagen Bank from 11-13 July 2011 from the WHOI coastal Research Vessel RV Tioga (Fig. 3). This location was easily accessible from WHOI, has water depths commensurate with the capabilities of the REMUS-100, which is depth rated to 100 m, and typically has diverse zooplankton assemblages. In addition, various species of both baleen and toothed whales are known to present at different times of the year. All operations were performed during daylight hours. Closely co-located (in time and space) MOCNESS net tows (a total of 3 tows with multiple nets per tow were performed) and VPR measurements were performed to directly groundtruth the acoustical backscattering measurements obtained with the WHOI broadband system (Fig. 4). The VPR was profiled together with a CTD and 10 casts were performed, often involving multiple profiles. A high-powered, cabled, broadband acoustical backscattering system developed by EdgeTech was pole-mounted and used to simultaneously collect broadband acoustical backscattering measurements. The frequency range of the broadband EdgeTech system (35 kHz-600 kHz) overlaps the lower portion of the frequency band for the WHOI broadband system (120-1250 kHz). The original goal was to also obtain coincident measurements with a more traditional multi-frequency narrowband system, but the system was undergoing repairs at the time of the cruise. The REMUS-100 missions varied in length from short 20-minute missions to 4-hour missions, and in complexity, starting from simple surface tracking along a single line with the vessel in close proximity, to long missions involving multiple depths (with and without bottom tracking) and missions while the ship was involved in other operations, such as performing a MOCNESS net tow and VPR/CTD casts. The REMUS-100 bioacoustics module was also used to image multiple internal waves, and to track a particularly large amplitude internal wave, illustrating the feasibility of rapidly re-programing for more versatility. Initially the transducers on the REMUS-100 were mounted downward facing and the REMUS-100 was programmed to maintain a fixed shallow depth (order 2-4 meters). However, much of the observed scattering at the field site was concentrated in scattering layers in the top 10 m of the water-column, so the transducers were eventually rotated so that they would be upward facing, and the REMUS-100 was deployed to greater depths to enable the shallow scattering layer to be imaged (Fig. 5).

To date, acoustic images consisting of both the raw (Fig. 5) and the matched-filter output (Fig. 6) have been generated for all channels for the entire duration of the field demonstration for both the REMUS-100 broadband acoustics module and the EdgeTech broadband data. The analysis of the acoustic data for spectral content is ongoing. Preliminary examination of the MOCNESS and VPR data indicate that abundances of zooplankton throughout the study site were not particularly high, and that numerical abundance of zooplankton was dominated by small copepods that were relatively evenly distributed throughout the water-column.

RESULTS

The primary result of this field demonstration was to successfully show that it is feasible to use broadband acoustic scattering techniques from an autonomous vehicle. The logistical aspects of this field demonstration were seamless. The REMUS-100 bioacoustics module measured broadband acoustic scattering using three octave bandwidth transducers covering the frequency range from 120 kHz to 1.25 MHz (with some gaps). The useful detection and imaging range was frequency-dependent, with maximum ranges at low-frequencies to about 15m, but with a useful range of less than 5 m at the higher frequencies. Over these ranges, the REMUS-100 bioacoustics module compared favorably qualitatively to the performance of a high-power, cabled, broadband system. Calculations of noise floors are currently underway.

A shallow acoustic scattering layer with what appeared to be a relatively flat spectrum was observed throughout much of the study site, typically correlated to the location of a sharp thermocline. However, there was no indication in either the MONESS or the VPR that the acoustic scattering layer was correlated to an increased abundance of zooplankton. Small copepods were distributed relatively uniformly throughout the water column and predicted scattering from these organisms (which is predominantly in the Rayleigh scattering regime for frequency range of the EdgeTech system) is not consistent with the observed scattering from either the REMUS-100 bioacoustics module or the EdgeTech system. In order to better image this scattering layer with the REMUS-100 bioacoustics module, the transducers were rotated on the REMUS-100 so that they would be upward facing. However, though both acoustic systems imaged the scattering layer and indicated a relatively flat frequency spectrum, as there was no indication from the MOCNESS or VPR that the scattering layer was due to zooplankton, it is speculated that the scattering layer was made up of either larval fish or bubbles entrained from breaking surface waves. This persistent layer was occasionally modulated by the passage of internal waves, and on one occasion an internal wave was tracked with both the shipboard system and the REMUS-100. The internal wave surface expression was used to determine the location of the internal wave, and the ship then steamed rapidly ahead of the internal wave and the REMUS-100 was deployed such that it performed a track line through the internal wave (Fig. 6). The REMUS-100 bioacoustics module was also deployed off the WHOI dock to image large and persistent schools of silverside (identified visually from the dock, typical individual about 10 cm in length), located in the upper 5-6 meters of the water column. Again, the REMUS-100 bioacoustic module gave similar results to the high-powered Edgetech system (Fig. 7). A primary outcome of this field feasibility test is that though scattering from fish was feasible and quantifiable, and measurable scattering levels were observed, the abundances of zooplankton were generally too low account for the measured scattering by either the low-power REMUS-100 broadband backscattering system or the higher power EdgeTech system.

Work remaining on this project includes 1) finalizing the calibration for the 1.5 ms transmit signals (the system is currently calibrated for the 500 μs transmit signal duration), 2) incorporating the calibration to allow spectra, and associated noise floors, to be calculated, and 3) with the current funding permitting, attempting an additional 1-day cruise to search for higher abundances of zooplankton.

IMPACT/APPLICATIONS

- This system represents a low-cost, autonomous, compact, broadband, high-frequency, acoustic backscattering system that has the potential to significantly reduce the well-known ambiguities in estimating biologically meaningful parameters associated with interpretation of traditional single-frequency acoustic backscattering measurements. We note that the sonar module (with transducer) can be fabricated for under $2k, representing a very low-cost, yet versatile, tool for the bioacoustics community.

- The broadband bioacoustics module here significantly enhance the capabilities of gliders and small AUVs for mapping distributions of highly-abundant zooplankton on ecologically relevant scales, with, for example, direct application to mapping the prey field of zooplanktivorous whales. In addition, this system could easily be used as a surface or bottom tracking device, or to map the distribution of bubbles or fish.

RELATED PROJECTS

None.

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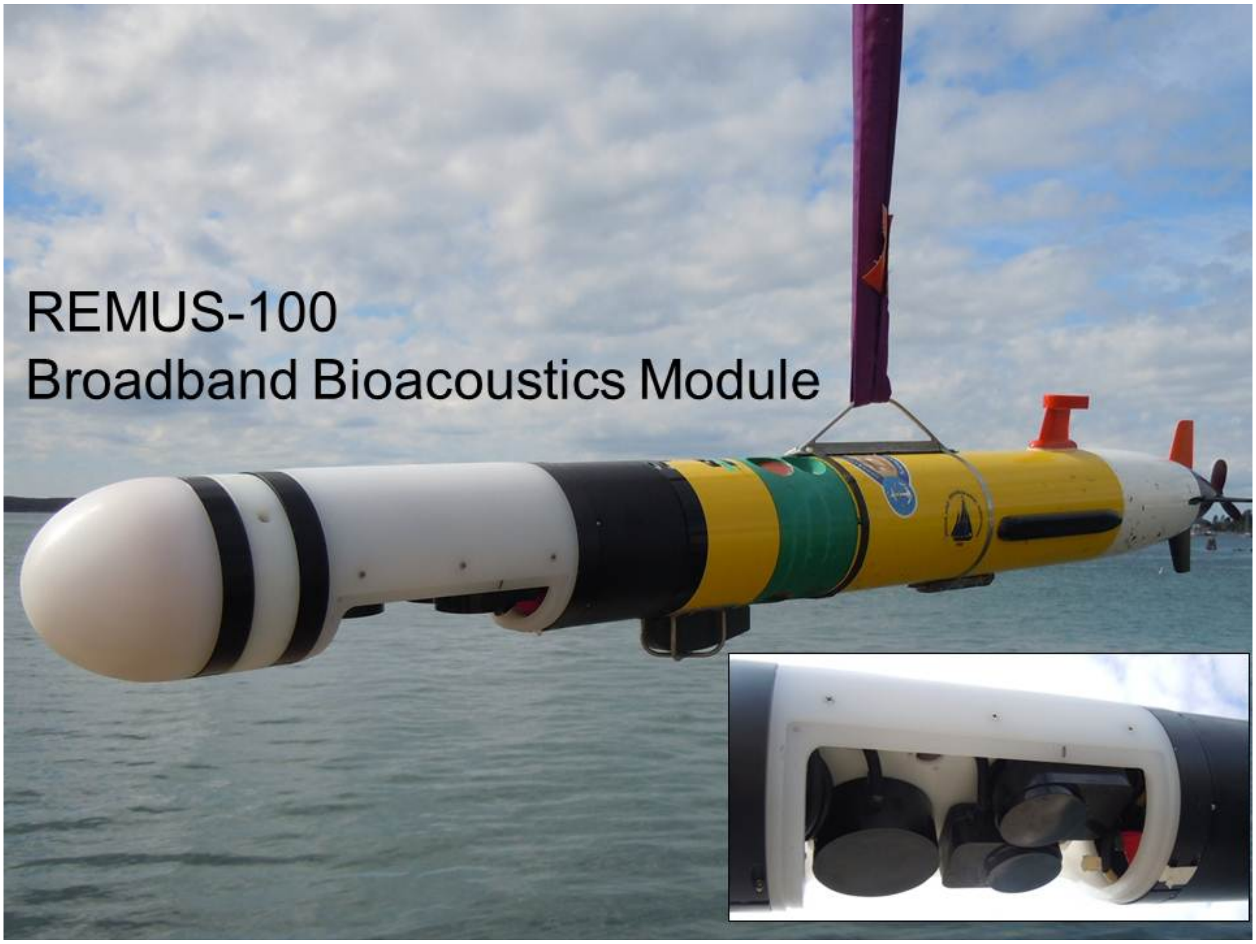

Fig. 1. Photograph of the REMUS-100 with the Broadband Acoustic Backscattering System: The "REMUS-100 Broadband Bioacoustic Module".

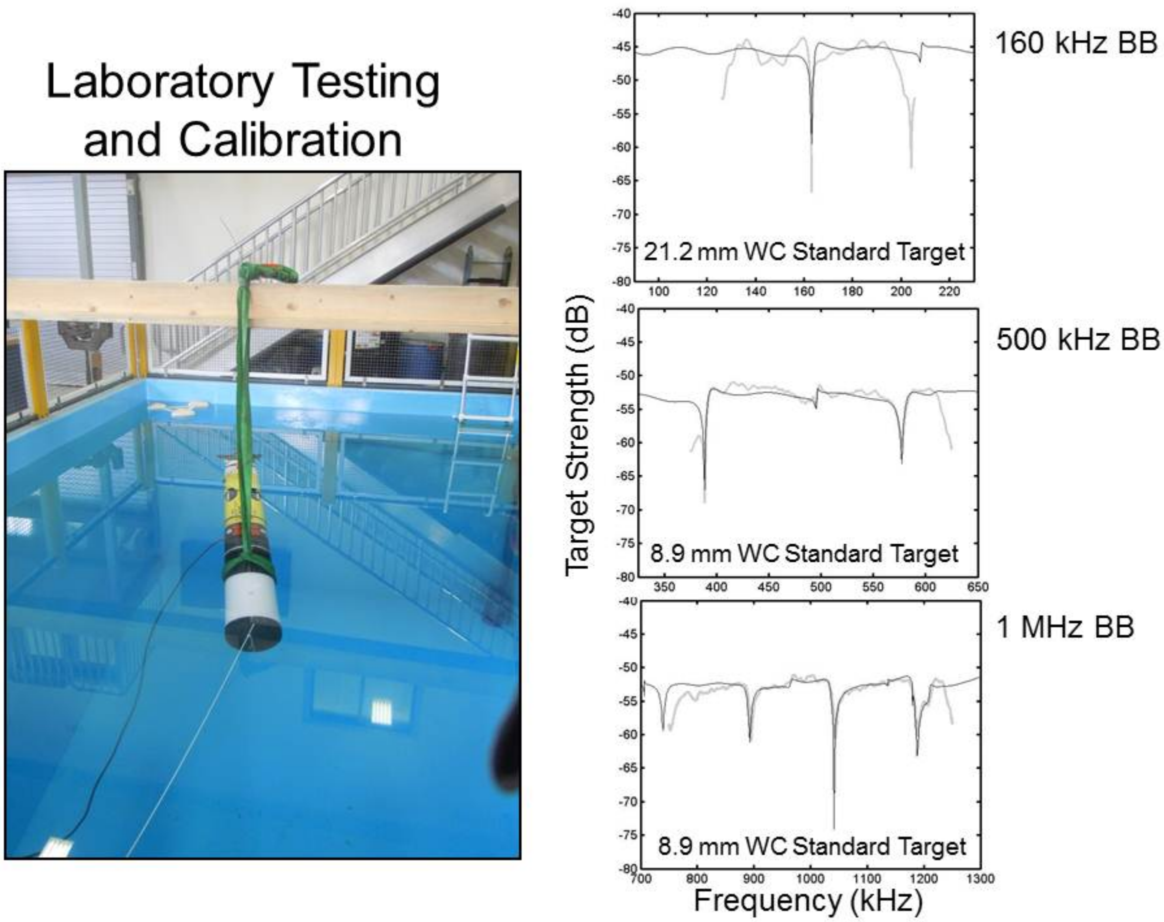

Fig. 2. Calibration of the REMUS-100 Broadband Bioacoustic Module in a 3-m-deep, salt-water tank at WHOI using a 8.9-mm and 21.2-mm diameter tungsten carbide (WC) standard targets. Right hand panels represent a comparison of the model series solution to the measured returns for the standard targets for the three broadband channels with center frequencies at 160, 500, and 1000 kHz.

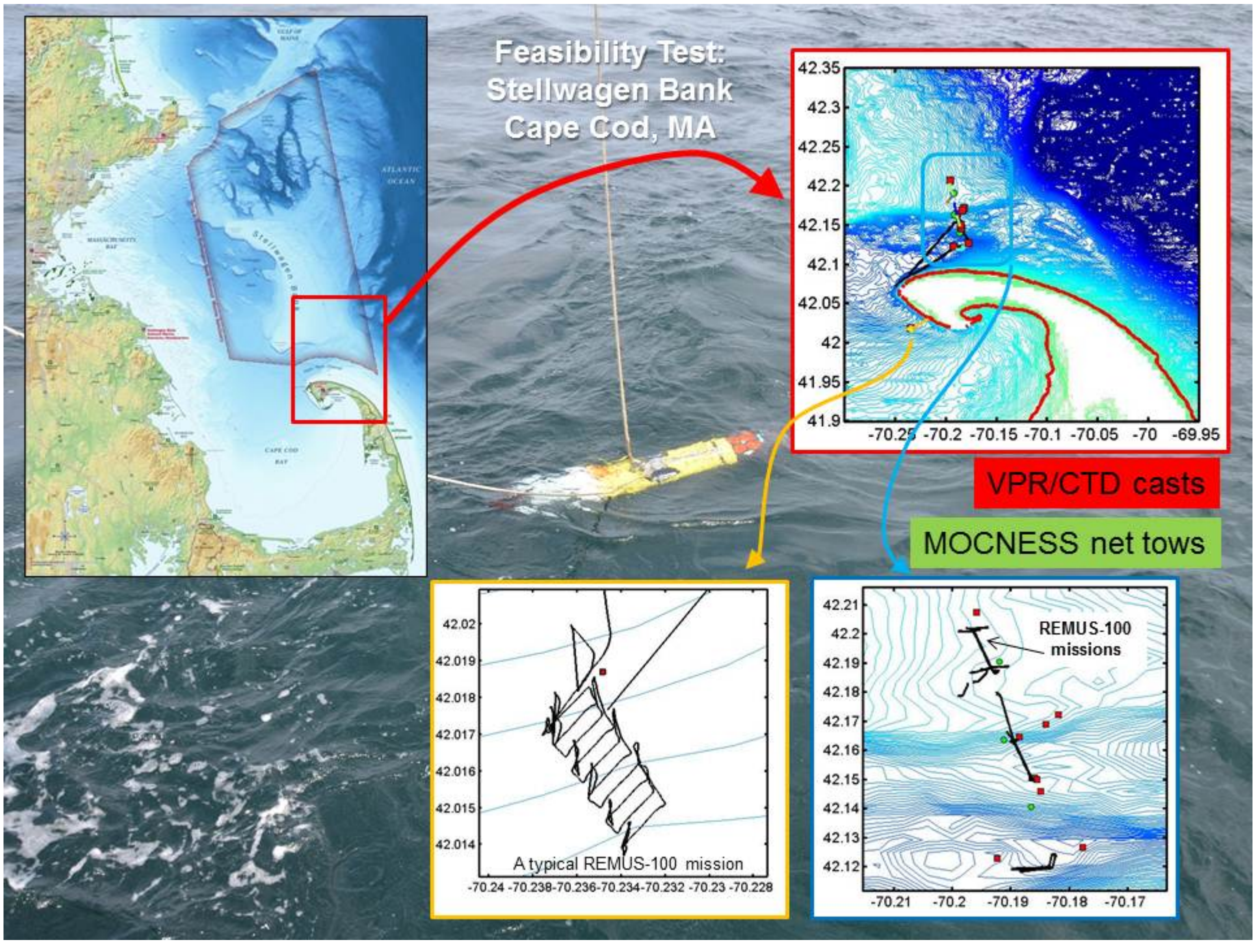

Fig. 3. Location of the field demonstration in and around Stellwagen Bank, Cape Cod, MA. The green circles show the locations of the MOCNESS tows, and the red squares show the locations of the VPR/CTD casts. The black lines indicate the locations of all 17 missions performed with the REMUS-100 during the 3-day field demonstration.

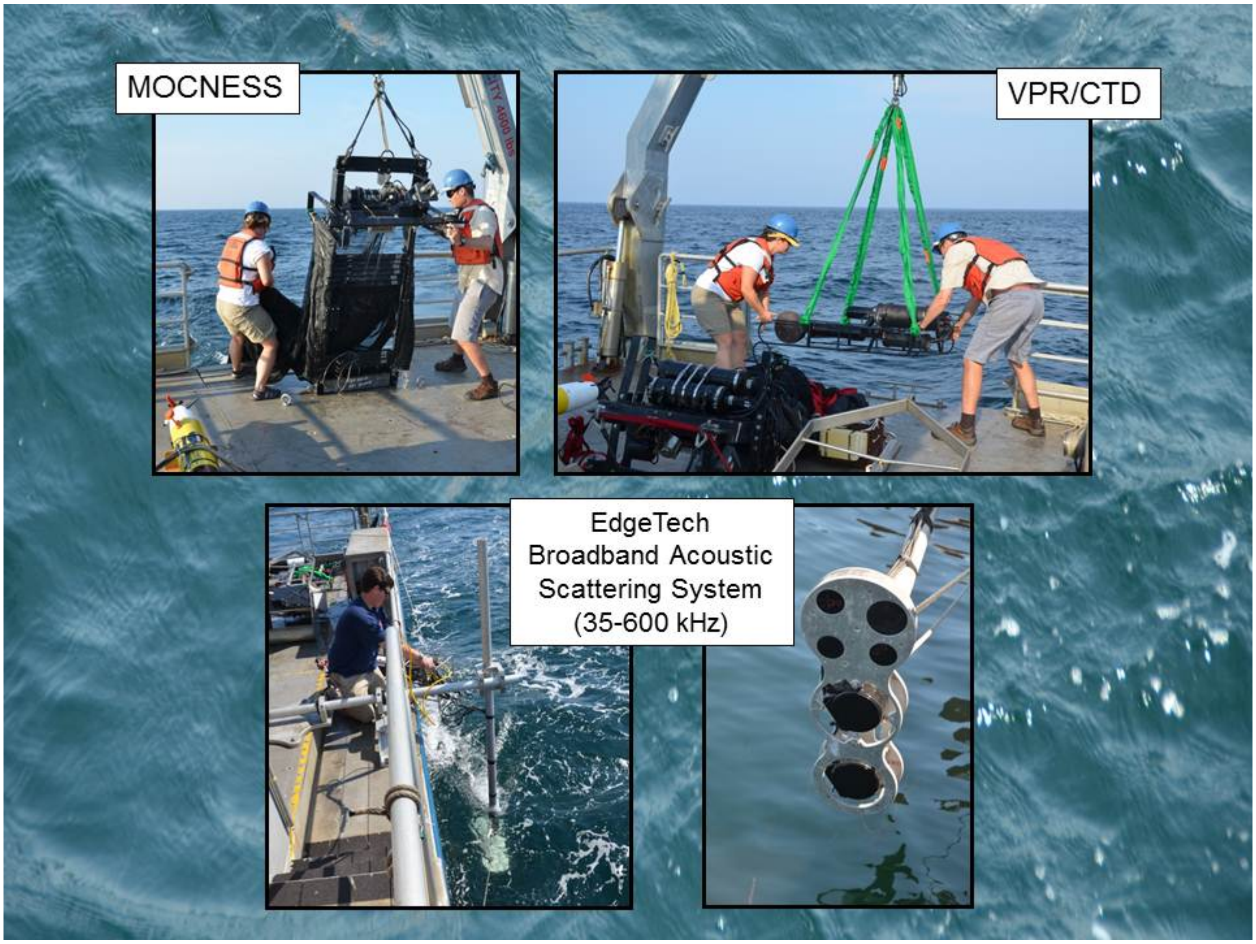

Fig. 4. Photograph of the instruments used to groundtruth the measurements performed with the REMUS-100 Broadband Bioacoustic Module: The MOCNESS, VPR, and pole-mounted, high-power, cabled, broadband acoustic EdgeTech system.

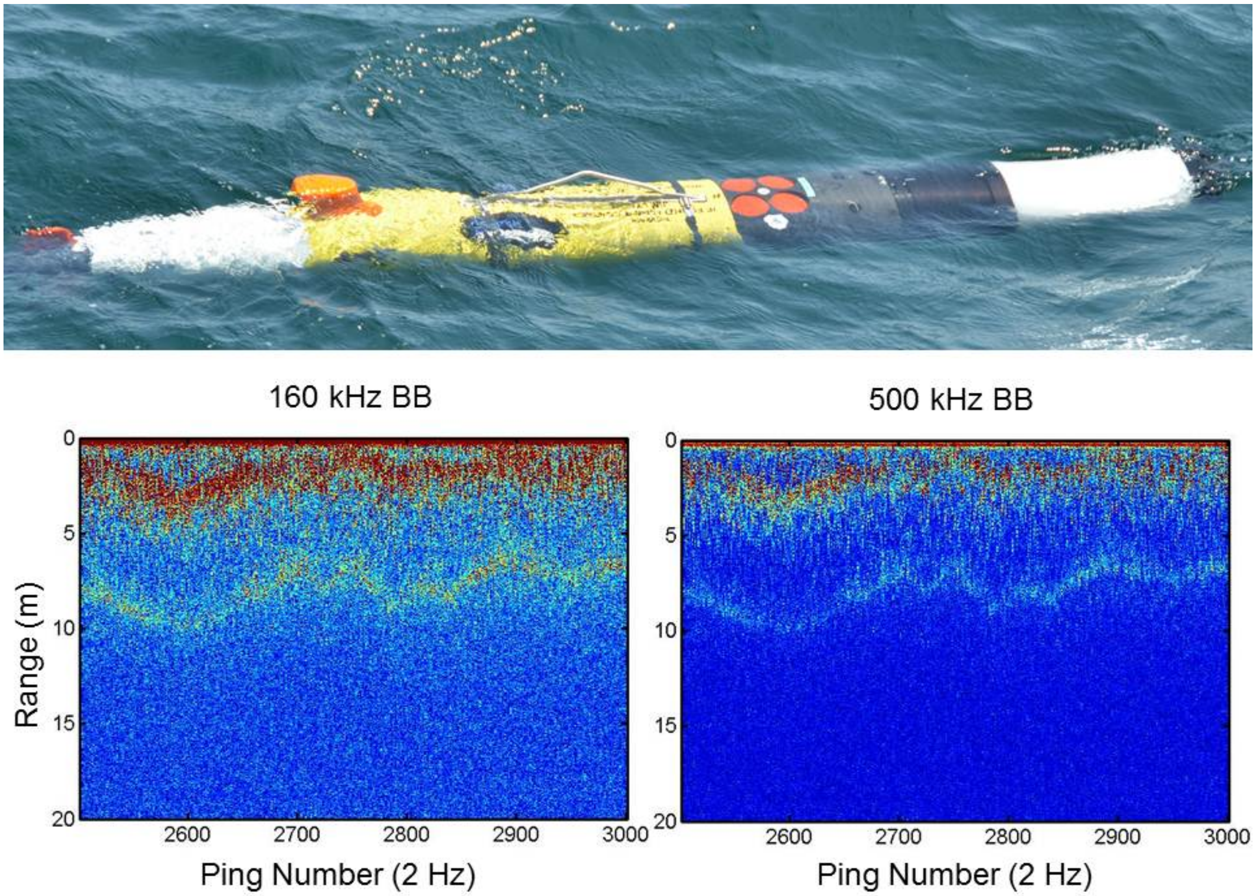

Fig. 5. Photograph of the REMUS-100 Broadband Bioacoustic Module with downward-looking transducers. Raw data for the 160 kHz and 500 kHz channels, showing a relatively persistent scattering layers located 3-4 m below the surface, and a weaker scattering layer located at about 8 m below the surface.

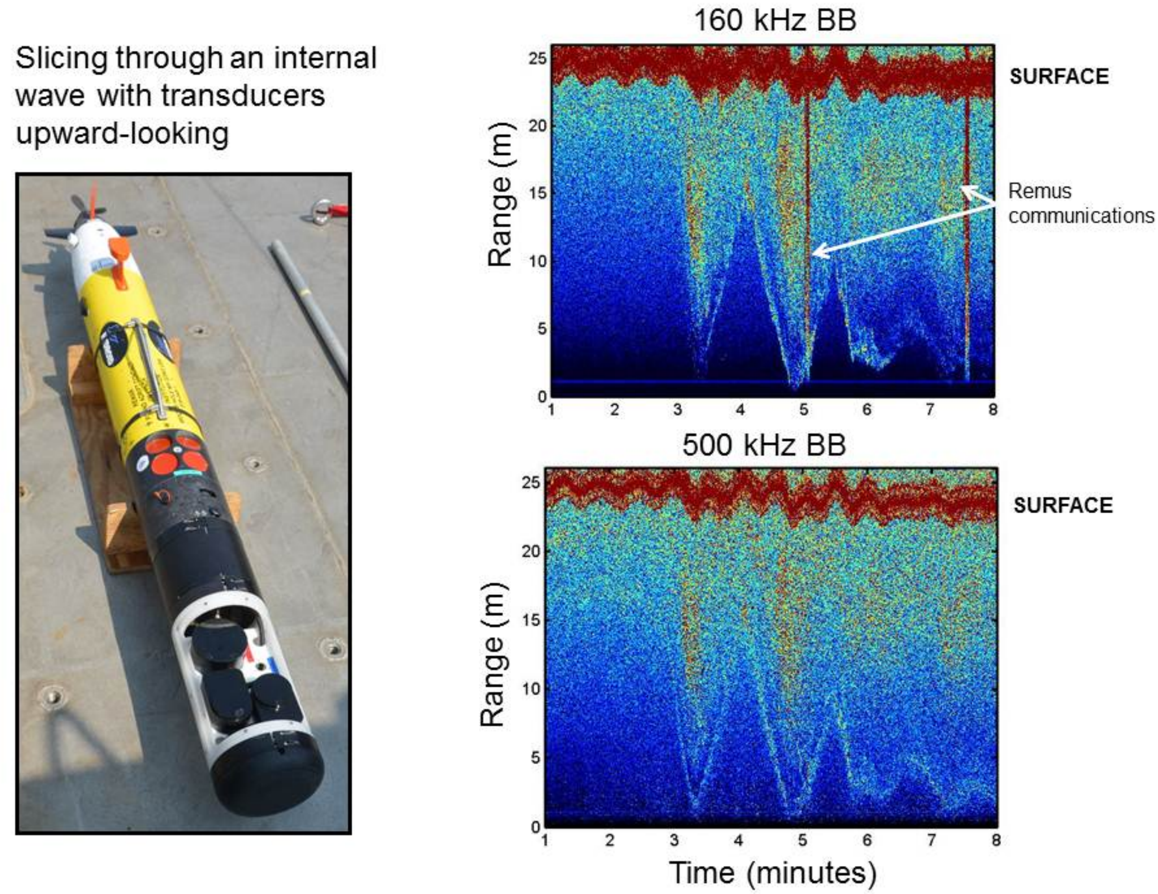

Fig. 6. Photograph of the REMUS-100 Broadband Bioacoustic Module with upward-looking transducers. Matched-filter data for the 160 kHz and 500 kHz channels with the REMUS-100 at 25 m depth, slicing through an internal wave. Noise pick-up from the REMUS-100 communications system was visible on the 160 kHz BB channel (vertical spikes).

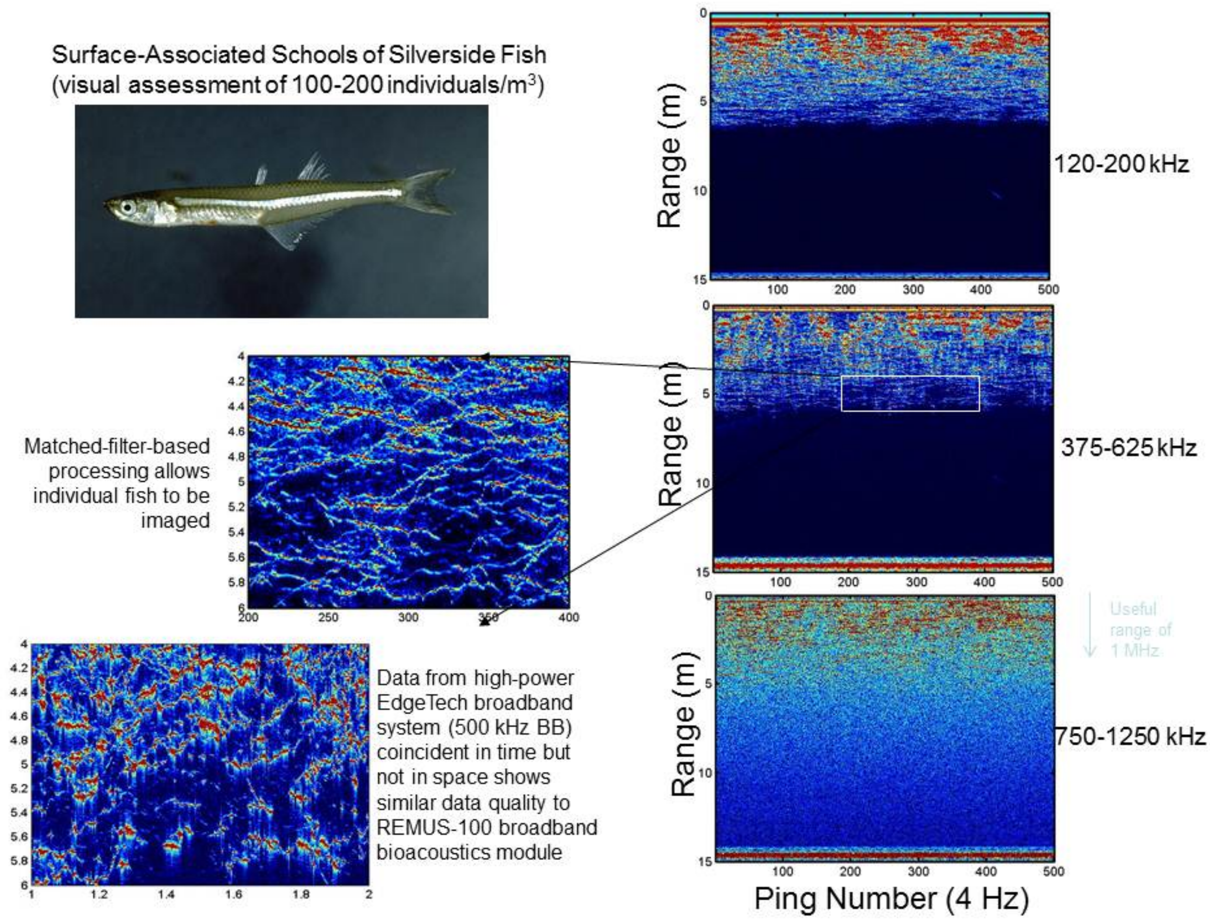

Fig. 7. Acoustical backscattering from a school of surface-associated silverside fish measured with the REMUS-100 Broadband Bioacoustic Module. Taking advantage of the increased range resolution associated with matched-filter processing, it was possible to image individual fish at close range even in schools with relatively high abundances.